Inverse Modeling of Coastal Tides

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AWARD #: N00149410926

http://www.oce.orst.edu/po/research/tide

LONG TERM GOALS

The principal goal of this project is to develop efficient, relocatable, tidal data assimilation schemes that make use of all information, including data (e.g., altimetry, current moorings, coastal radar) and dynamics to constrain barotropic and internal tides (especially tidal currents) in coastal areas and shallow seas.

OBJECTIVES

Objectives in the current project period are: (1) to adapt the computationally intensive methods developed by Egbert et al. [1994] into a relocatable inversion package for routine application to regional and coastal barotropic tidal modeling; (2) to apply these methods to study tidal currents off Oregon coast where extensive current meter and coastal radar data are available; (3) to begin development of tidal inversion methods for a three-dimensional stratified ocean.

APPROACH

We have used a rigorous variational approach to data assimilation, based on minimizing a penalty functional defined in terms of weighted misfits to available tidal data, and the hydrodynamical equations. The weighting of data and dynamics is defined by rational estimates of errors in the two types of information. To solve the inverse problem we use variants on the explicit representer approach described by Bennett [1992]. A major challenge (and a focus of much of our effort) has been to develop more efficient solution methods, to allow for larger data sets, higher resolution, and routine rapid application to smaller scale problems. To develop a three-dimensional tidal inversion, we have begun using a non-linear primitive equations model, the Princeton Ocean Model (POM) for tidal modeling studies.

WORK COMPLETED

A major focus of effort over the past year has been on refinement of the OSU Tidal Inversion Software (OTIS) package. OTIS is a self-contained efficient barotropic tidal inversion package, based on a relocatable implementation of the TOPEX/POSEIDON variational assimilation scheme described in Egbert, Bennett & Foreman [1994] and Egbert (1997). The approach that we have developed uses a reduced set of representers, which are calculated by solving the linearized frequency domain shallow water equations (SWE) by factoring the matrix of coefficients for the elevation wave equation. All

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 1999**	2. REPORT TYPE	3. DATES COVERED **00-00-1999 to 00-00-1999**

4. TITLE AND SUBTITLE **Inverse Modeling of Coastal Tides**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Oregon State University,College of Oceanic and Atmospheric Sciences,104 Oceanography Admin Bldg,Corvallis,OR,97331**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

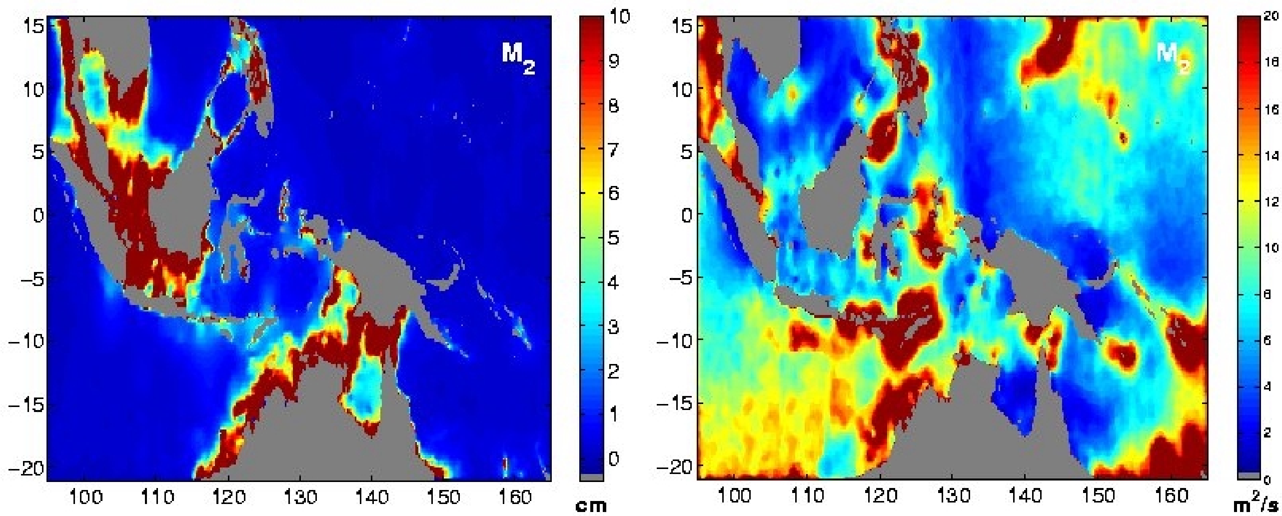
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

available altimeter data in a modest sized area (e.g., 20 degrees by 20 degrees) can be assimilated into an 8 constituent 1/12 degree barotropic tidal model using a high-end workstation with approximately 500 Mb of memory. Clock time required for the whole process is less than a few hours. The package includes all programs needed for setting up grids, defining prior dynamical error covariances, pre-processing of TOPEX/POSEIDON altimeter data, and computation of the inverse solution. Data bases for bathymetry, boundary conditions, and altimeter data are included. Documentation and tar files containing source code and databases are available over the internet at http://www.oce.orst.edu/po/research/tide .

Over the past year OTIS was demonstrated and installed on computers at NRL/SSC, and at NASA/GSFC.   Based on experiences with these demonstrations and on feedback from initial users a number of modifications of OTIS were made to enhance ease of use. For example, an editable "run parameter" file now can be used to control all options to ensure consistency of all steps. Execution of a simple script will complete the full inversion process using options defined in this file, once initial interactive grid set up steps are completed.

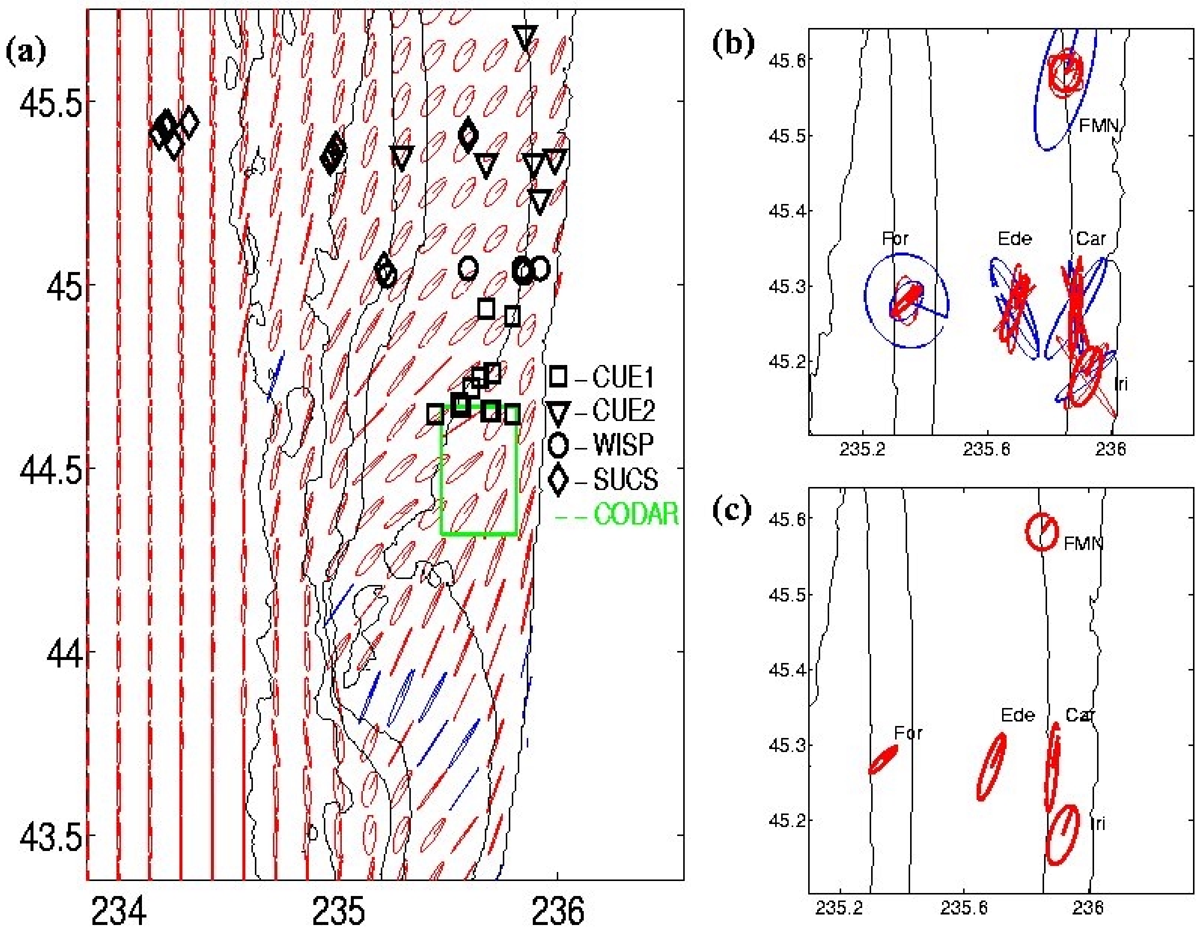
We have also made a number of significant improvements to OTIS. Users now have a choice of specifying elevation or normal-flow open boundary conditions (BCs).   Both types of BC are fully supported throughout.   We have made improvements to the non-linear (time-step) forward solution, now allowing for non-linearity in the continuity equation, including the effect of drying in shallow coastal areas. A more rigorous treatment of ocean loading and self-attraction effects has been incorporated, with global data bases of corrections for these terms for all major constituents now an integral part of OTIS.



1: Standard deviations of M2 constituent of inverse solution for Indonesian seas. Left: elevations. Right: N-S volume transports.

Implementation of posterior errors has now been fully implemented and tested. Automatic re-scaling of prior data and dynamical error variances has been implemented to make these consistent with misfits of the prior solution to the data and dynamics. Programs to compute error variances for tidal elevations and currents are included with OTIS.   An example for the area around Indonesia is shown in Figure 1. We have also made significant improvements to the prior error covariance to better account for the effects of islands and unresolved bottom topography on errors in the numerical tidal solutions. Based on extensive modeling of tides at varying resolution, we have constructed a simple empirical spatially dependent estimate of the magnitude of these errors in the equations. Other improvements to the prior covariance include allowing different decorrelation length scales for BC and dynamics.

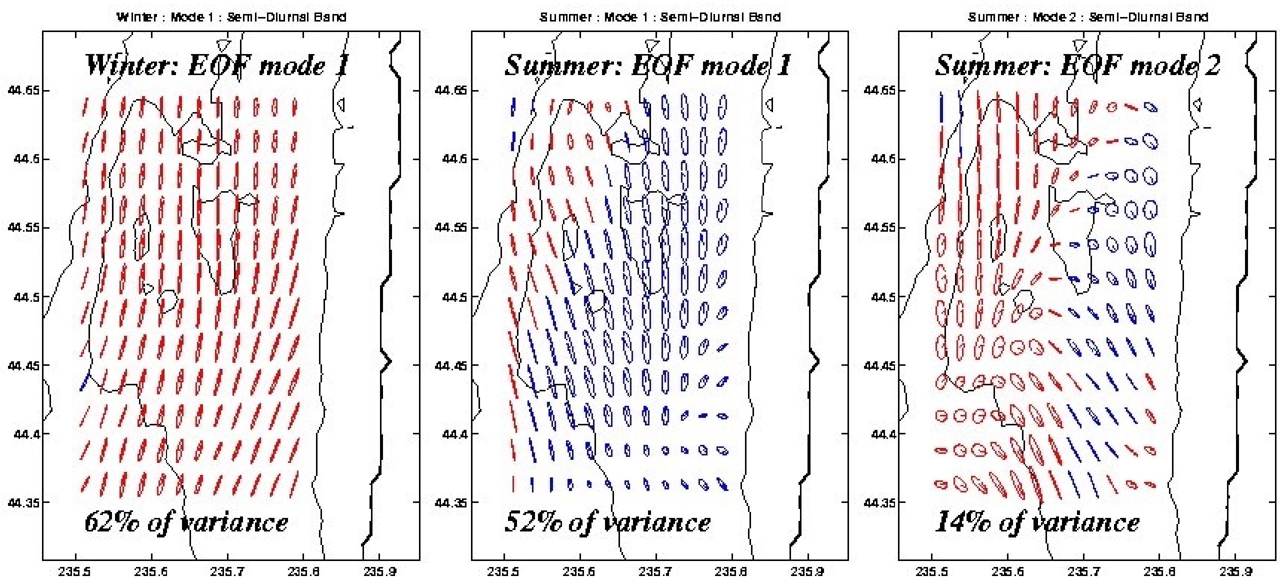
A second major effort has involved inversion of historical current meter data and high frequency (HF) coastal radar data off the Oregon coast (Figure 2). To do this we have fully implemented current data inversion into OTIS. A significant challenge has been extracting reasonable estimates of barotropic currents from the time series. We have encountered two problems: measurements of currents are at only a few depths, or on the surface; and signals in the tidal band are intermittent.



2: Tidal ellipses (red are clockwise, blue counterclockwise) for M2 currents of the Oregon coast. (a) Inverse solution, showing location of current moorings and area covered by HF radar (green box). (b) current ellipses for the CUE1 current moorings (all depths). Estimated barotropic current ellipses obtained as described in the text.

Simple harmonic analysis of the time series often yields poor results that are inconsistent between nearby sites, or even at the same site from different times. We have developed a scheme based on complex demodulation of the time series, using an admittance approach so that only a single complex parameter must be estimated (as a function of time) diurnal and semi-diurnal bands. Estimates of tidal variations can then be obtained with a resolution of 2-4 days, and these can be weighted in the final estimate of tidal harmonic constants to emphasize those time periods where tidal currents are most nearly barotropic. Using this scheme we have obtained consistent and well-behaved harmonic constants for tidal currents off the Oregon coast (Figure 2).

The addmittance/complex demodulation approach also allows us to look at variability over time of coherent tidal band spatial structure in the HF radar data. EOFs of the complex demodulates are shown in Figure 3. This shows that only a single spatial pattern, which is reasonably consistent with the barotropic tidal solution is seen in the winter. More complex tidal variability is seen in the summer during upwelling.



3: EOFs computed from semi-diurnal band complex demodulates of Newport HF radar data. In winter there is only one dominant EOF, which appears very similar to the assimilation solution (based on historical current moorings only). In summer tidal band currents are more complex.

We have begun using the Princeton Ocean Model (POM) to look at the generation of internal tides off the Oregon coast. Initial efforts show significantly less internal tide in POM runs than we observe in data. A major challenge is that we need open boundaries to specify the tidal forcing. Recent progress running POM for a wind driven circulation with open boundaries by Prof. J. Allen's group should allow us to do more realistic modeling of internal tides off the Oregon coast with POM. Finally, over the past year the PI (Egbert) has been involved fairly extensively in working with J. Allen and R. Miller on assimilation of HF radar data for the sub-inertial wind forced circulation.

RESULTS

The most important results of this project overall relate to the methodology of data assimilation. We have demonstrated that a rigorous variational approach to data assimilation can be practical.

Over the past year we have found that using normal flow BC can significantly improve the tidal assimilation solutions, especially for currents. Also, experiments with a variety of different prior model covariances have demonstrated the importance of this input assumption. Allowing for realistic error amplitudes and correlation length scales to account for unresolved topography significantly improves fits to altimeter data in areas such as Indonesia. A major challenge for routine operational use of a scheme like this is generation of the “correct” prior error covariance in a manner that is both generally applicable and easy to use.

Our initial investigation of internal tides on the Oregon shelf demonstrates that internal tides in this area are intermittent, and probably depend on the changing stratification and the lower frequency “background” flow. Efforts to model internal tides with POM, using realistic initial stratification, produces little internal tide on the narrow Oregon shelf. Significantly larger baroclinic oscillations are often observed in the current meter and HF radar data in the tidal band. We have concluded that understanding this discrepancy and developing assimilation methods for baroclinic tides will require integrated studies of the tidal and sub-inertial bands

IMPACT/APPLICATIONS

The methods developed in this project have already had significant application and impact. Other groups working on tidal modeling have adopted our approach (e.g., LeProvost et al., 1997) to tidal data inversion. Perhaps more importantly, some of the efficient solution methods developed during this project have also been applied to other oceanographic assimilation problems (e.g., Bennett et al., (1996) have used similar data space conjugate gradients methods.

TRANSITIONS

The OSU tidal inversion software (OTIS) is now documented well, relatively easy to use, and can be run with only modest computing resources. It is available to all interested parties over the intenet. OTIS has been demonstrated and installed at NRL/SSC and NASA/GSFC. Several groups at NRL have expressed interest in using OTIS to generate barotropic tidal BC for coastal applications.

RELATED PROJECTS

With NSF/NASA funding I am collaborating with R. D. Ray of NASA/GSFC on a study of global tidal dynamics using satellite altimeter data. Improvements to inversion methods and software will be to some extent transferable from this NSF project to ONR funded research on coastal tidal modeling, and vice-versa. We are also working with Profs. J. Allen and R. Miller, and post-docs Peter Oke and Alexandre Kurapov to develop practical assimilation methods for coastal HF radar data.

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PUBLICATIONS

Scott, R.K., Allen, J.S., Egbert, G.D., and R.N. Miller, Assimilation of surface current measurements in a coastal ocean model, submitted to *Jour. Phys. Ocean.*, 1999.